

On the relationship between the continuum of interstellar extinction curves, the 2200 Å bump, and the diffuse interstellar bands

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ABSTRACT

A previous article argued that the antagonism between sight-lines with and without a bump at 2200 Å disappears and the observed properties of interstellar extinction can be globally understood if it is accepted that scattered starlight contaminates the observed spectrum of reddened stars. The present paper provides a better understanding of the characteristics of this scattered light, and examines the consequences of this revision of interstellar extinction theory for the 2200 Å bump and the diffuse interstellar bands (DIBs) questions. Two implications are worth noting: (1) the effect of interstellar extinction on cosmic distance estimations needs to be reconsidered in light of the new paradigm of interstellar extinction; (2) hypothetic particles, such as the Poly Aromatic Hydrogenated molecules, the existence of which has never been proven, are unnecessary to explain the peculiarities of interstellar extinction. Hydrogen, by far the most abundant constituent of interstellar clouds, should alone account for the three major features of interstellar extinction: the departure of the continuum from linearity, the bump, and the DIBs.

Subject headings: ISM: lines and bands; planetary nebulae: general — Physical Data and Processes: astrochemistry — Physical Data and Processes: radiative transfer — Physical Data and Processes: scattering — ISM: dust, extinction — ISM: lines and bands

1. Introduction

After decades of research and despite a now well-established set of observations, studies on interstellar extinction face the unusual predicament of not having developed a firm and self-consistent theoretical framework. Nearly fifty years after the discovery of the unexpected ultra-violet spectrum of reddened stars, the nature of the particles which would explain the 2200 Å bump or the far-ultraviolet extinction curve remains controversial. In the visible wavelength range, the carrier(s) of the diffuse interstellar bands (DIBs) are still unidentified a century after their first detection.

The basic paradigm underlying interstellar extinction studies is that an observer sees the direct light from reddened stars dimmed by different types of interstellar particles on the line of sight (Sect. 4). However, this paradigm leads to logically unsustainable contradictions between theory and observations at ultraviolet wavelengths (Za-

gury (2013), Sects. 5 to 7 this paper).

An alternative, the only one in fact, would be to accept that a large amount of scattered starlight is mixed with the direct light we receive from reddened stars (Zagury 2013). This would unify existing observations in a consistent picture, simplify the true extinction law of interstellar dust (which is linear over the whole spectrum, $\tau_\lambda \propto 1/\lambda^p$, $p \sim 1$), explain that some extinction curves have no 2200 Å bump and continue to be linear in the ultraviolet (Fig. 1), explain the observed relationship between the extinctions in the optical and in the ultraviolet parts of the spectrum, and settle long lasting controversies on the value of the total to selective extinction R_V parameter (Sect. 10).

The alternative is itself not free from difficulties. If light received from a reddened star splits into a direct and a scattered light components, the latter can overwhelm the former. In the ultraviolet a star would appear much brighter if it could be observed through an interstellar cloud of pure gas

(no dust) than it would without the cloud on the line of sight. The cloud (with no dust) amplifies the signal from the background star and acts more like a lens than as an extinction medium. On observed extinction curves the effect is masked by the exponential extinction $e^{-\tau_\lambda}$ ($\tau_\lambda \propto 1/\lambda^p$, $p \sim 1$) interstellar dust introduces. It is recovered when the latter is removed (Fig 2).

The specificity of diffraction in the forward direction is well known and recognized. It justifies the importance of the scattering component in the spectrum of reddened stars, although no theory provides a straightforward fit to interstellar extinction curves. Textbooks (Hecht 2003; Stone 1963) discuss and illustrate the pattern of forward diffracted light by randomly distributed particles, but remain at a qualitative level. The formula for the irradiance of the forward scattering by a slab of identical particles, derived by H.C. van de Hulst in the 1950s, seems to anticipate the lensing effect of interstellar clouds but predicts ratios of the scattered to the direct starlight intensities that are much too high, and a different wavelength dependence than observed (Zagury & Pellat-Finet (2012) and Sect. 11.1).

This revision of the understanding of the continuum of extinction curves represents an important development in interstellar extinction research, moving it from a questioning of the chemistry of the interstellar medium to a problem of optics. It also renews the insight into two major issues cited above, the 2200 Å bump and the DIBs. The bump, a most singular figure in the ultraviolet part of extinction curves, must be seen as an interruption of the scattered light component of the spectrum of reddened stars (Sect. 13 and Fig. 1).

In 2005 the state of DIB research was summarized as follows:

In May of 1994, the first major conference focusing entirely on the baffling problem of identifying the carriers of the diffuse interstellar bands (DIBs) was held at the University of Colorado, Boulder... From even a perfunctory reading of the subsequently published book (Tielens & Snow 1995) containing the invited papers presented at the meeting, one would gather that there was a growing

sentiment among the conference participants that the DIB carriers would soon be shown to be large, complex molecules. More than ten years have now passed since the Boulder conference was held. Despite intensified, technically sophisticated efforts... to identify such molecules made during this period by several world class teams of astronomers, chemical kinetists, and spectroscopists, the situation remains today exactly as it was in 1994 - i.e. not a single band in the total DIB spectrum (now known to contain more than 250 bands) has been convincingly assigned to an optical transition of any molecule, atom, or ion! (Sorokin & Glowina 2005)¹.

As sensitivity and spectral resolution of observations increase, new DIBs (now over 500, see Hobbs et al. (2009)) continue to be found, but, over ten years later and twenty years after the Boulder meeting, the identification of the "large, complex molecules" that would explain the features is at a standstill. Neither fullerenes (Campbell et al. 2015) nor Poly Aromatic Hydrogenated molecules (PAHs) will account for the whole DIB spectrum and the presence of these molecules in interstellar clouds raises abundance difficulties (Sect. 14.2 and Ubachs (2014)). The situation is all the more paradoxical in that interstellar clouds sampled in extinction observations are known to be cold and close to vacuum regions of interstellar space, which leaves little room for a sophisticated chemistry.

The first part of this article (Sects. 3 to 11) deals with the continuum of extinction curves. A special emphasis is given to a critical issue, the number of free parameters, or degrees of freedom, that interstellar extinction curves depend on. The mutual exclusion between a theory that requires a minimum of six independent parameters (Sect. 4), and observation which shows that one is enough (Sect. 5), does not seem to be well integrated even in recent publications and textbooks (Sect. 6). The remarkably deterministic shape of extinction curves will also be difficult to accommodate with

¹Similar appreciations can also be found in Tielens (2008); Draine (2009).

the presence in interstellar clouds of different types of particles, the proportions of which can fluctuate independently one from the other (Greenberg 2000).

The observed properties of the scattered component of extinction curves are analyzed from Sects. 7 to 10. Sect 11 treats issues such as the limits of van de Hulst's formula and energy conservation.

Sect. 12 emphasizes the link between the scattered component of extinction curves, the 2200 Å bump, and the DIBs. The fact that the scattered component of extinction curves is coherent light may renew the interest for the DIB mechanism suggested by P. Sorokin and collaborators (Sect. 13).

Two implications of these views on interstellar extinction theory, for distance estimates and concerning the search of hypothetical particles of the interstellar medium, are drawn in Sect. 14.

An appendix summarizes elementary principles and particularly useful results of diffraction theory. The small vibrations of the hypothetical "particules éclairantes" (or "molécules étherées" (Fresnel 1866, p. 202, 375)) that Fresnel imagined to account for the propagation of light, still underlying modern presentations of classical diffraction theory (Feynman et al. 1964; Born 1999; Hecht 2003), should find an even more realistic application in coherent Rayleigh scattering than they do for the free propagation of light.

2. Interstellar extinction curves

Extinction curves A_λ have been introduced as the magnitude of the ratio F/F_{ref} of the spectrum F of a reddened star to the spectrum F_{ref} of a non-reddened star of same spectral type: $A_\lambda = -2.5 \log(F/F_{ref}) + C$. Constant C is eliminated by referring the extinction to a given wavelength (Zagury 2012). Extinction curves are usually normalized by the reddening $E(B - V) = A_B - A_V$ of the star. Reddening $E(B - V)$ estimates the column density of interstellar matter between the star and the observer, and normalized extinction curves the extinction per unit reddening in the direction of the star.

In a pure extinction process A_λ is nearly the wavelength-dependent optical depth τ_λ in the expression $F/F_0 = e^{-\tau_\lambda}$ of the attenuation of light

traversing a medium. It is a convenient parameter to characterize the particles on the line of sight and their column density. If different particles or media are on the line of sight, F/F_0 is the product of the $e^{-\tau_\lambda}$ over the particles and media, and the extinction curve is the sum of the extinctions A_λ .

These properties justify the fact that from the very beginning A_λ has systematically been preferred to F/F_{ref} (given by observation) as the variable for interstellar extinction observations. The choice, however, impacts the representation of extinction curves and affects how they are interpreted. The replacement of F/F_{ref} by A_λ can be particularly misleading if the pure extinction of starlight is not the only process at work.

Both understandings ($\propto F/F_{ref}$ or $-2.5 \log(F/F_{ref}) + C$) can be used to designate an extinction curve since the context generally avoids confusion. A 'linear' (or quasi-linear) extinction law means that the wavelength dependence of the extinction is $\tau_\lambda \propto 1/\lambda^p$ and equally that the attenuation of light is $F/F_{ref} \propto e^{-a/\lambda^p}$ ($p \sim 1$). Constant a can be simply related to the reddening $E(B - V)$ for any value of the total to selective extinction ratio $R_V = A_V/E(B - V) = \tau_V/(\tau_B - \tau_V)$ (Zagury & Turner 2012).

3. Observed properties of interstellar extinction curves

Within 1 to 0.4 μm in the visible wavelength range, all extinction curves follow a linear extinction law $\tau_\lambda \propto 1/\lambda^p$, $p \approx 1$ ($F/F_{ref} \propto e^{-a/\lambda^p}$). The linearity of the extinction tends to break under 400 nm, as if there was less extinction than predicted by the continuation of the linear law into the near-ultraviolet domain (Nandy 1964; Zagury 2012).

In the ultraviolet most extinction curves exhibit a singular broad absorption-like band centered close to 217.5 nm, the 2200 Å bump (bottom plot of Fig. 1). Curves with a bump have been most studied but, as Fig. 1 clearly demonstrates, extinction curves are not all bump-like. Some extinction curves do not have a bump, and when this is so the curves are always linear down to the bump region (middle plot of Fig. 1). In some cases the curves continue to be linear over the entire visible to ultraviolet wavelength range (top plot of Fig. 1).

Observation thus separates three classes of extinction curves: bump-like; linear down to the near-ultraviolet (the bump region); and linear over the whole visible-ultraviolet wavelength range (Fig. 1). The International Ultra-violet European (IUE) telescope has observed hundreds of reddened stars: with no exception, all extinction curves, whether they are observed in the Galaxy or in the Magellanic Clouds (Zagury 2007), fall into one of these three categories.

Extinction curves that are linear in the ultraviolet deserve special attention. They are more frequently observed in the Magellanic Clouds but are also present in the Galaxy. Other than that there is no fundamental difference between Magellanic and Galactic extinction curves (Zagury 2007).

In the Galaxy linear extinction curves are observed in two circumstances only: when the reddening is very low and when the obscuring interstellar matter is close to the star (for instance planetary nebulae) (Sitko et al. (1981); Seab et al. (1981); Zagury (2005, 2013)). At extremely low reddening (e.g. less than 0.08 mag.) extinction curves are always linear over the whole visible-ultraviolet wavelength range (Zagury 2001b).

It is clear from Fig. 1 that extinction curves with a bump and linear extinction curves anticorrelate: the bump disappears when and only when the linearity of the extinction in the visible extends to the near-ultraviolet or farther. Fig. 1 also shows that reddening is not enough to fix the threshold above which an extinction curve switches to non-linearity: the shape of an extinction curve is not determined by $E(B - V)$ alone. One or more additional parameters are needed to fully describe an extinction curve.

4. Interstellar extinction curves in the standard framework

Interstellar extinction curves have been analyzed under the assumption that the light we receive from the direction of a reddened star is the direct light from the star, extinguished by interstellar particles on the line of sight.

Under this assumption three types of particles, each having its own extinction law, are both necessary and sufficient to account for the variations of the extinction with direction (Greenberg 2000). The linear extinction law in the visible part of the

spectrum was early justified by a size distribution of interstellar grains (Greenstein 1938). The bump and the far-ultraviolet region are supposed to result from the extinction by two different species of molecules which still await a formal identification. Greenberg & Chlewicki (1983) found that the far-ultraviolet rise of extinction curves does not correlate with either the visual extinction or the 2200 Å bump. Several articles (for instance Meyer & Savage (1981); Massa & Fitzpatrick (1986)) have shown that the bump was only partially, and not univocally, related to the visual extinction.

No connection to environment was ever established that would explain the variations of the extinction in the three spectral domains. Linear extinction laws exist in nature (atmospheric aerosols) but no laboratory experiment has yet reproduced bump-like extinction curves.

The independent variations of the three types of particles required by standard extinction models was further supported by the mathematical analysis of Fitzpatrick & Massa (1988): should three separate extinction laws (one for the visual extinction, one for the bump, and one for the far-ultraviolet rise) rule interstellar extinction, interstellar extinction curves must depend on a minimum of six independent parameters in addition to $E(B - V)$.

5. The CCM paper and its one parameter fit

In contradistinction with the ideas that prevailed earlier (Sect. 4) Cardelli, Clayton, & Mathis (1989) (CCM hereafter) arrived at the remarkable and paradoxical conclusion that the variations of normalized extinction curves in different directions are well correlated over the whole spectrum. Another study, based on a larger sample of stars, reached the same conclusion a few years later (Bondar et al. 2006). CCM deduced that all normalized extinction curves with a bump can be approximated by a common fit that depends upon a single parameter, assumed to be R_V . The CCM fit has no physical basis and remains purely empirical.

The CCM paper, a breakthrough in the study of interstellar extinction, also became the source of several difficulties. The most obvious one is that it remains embedded in the conventional view

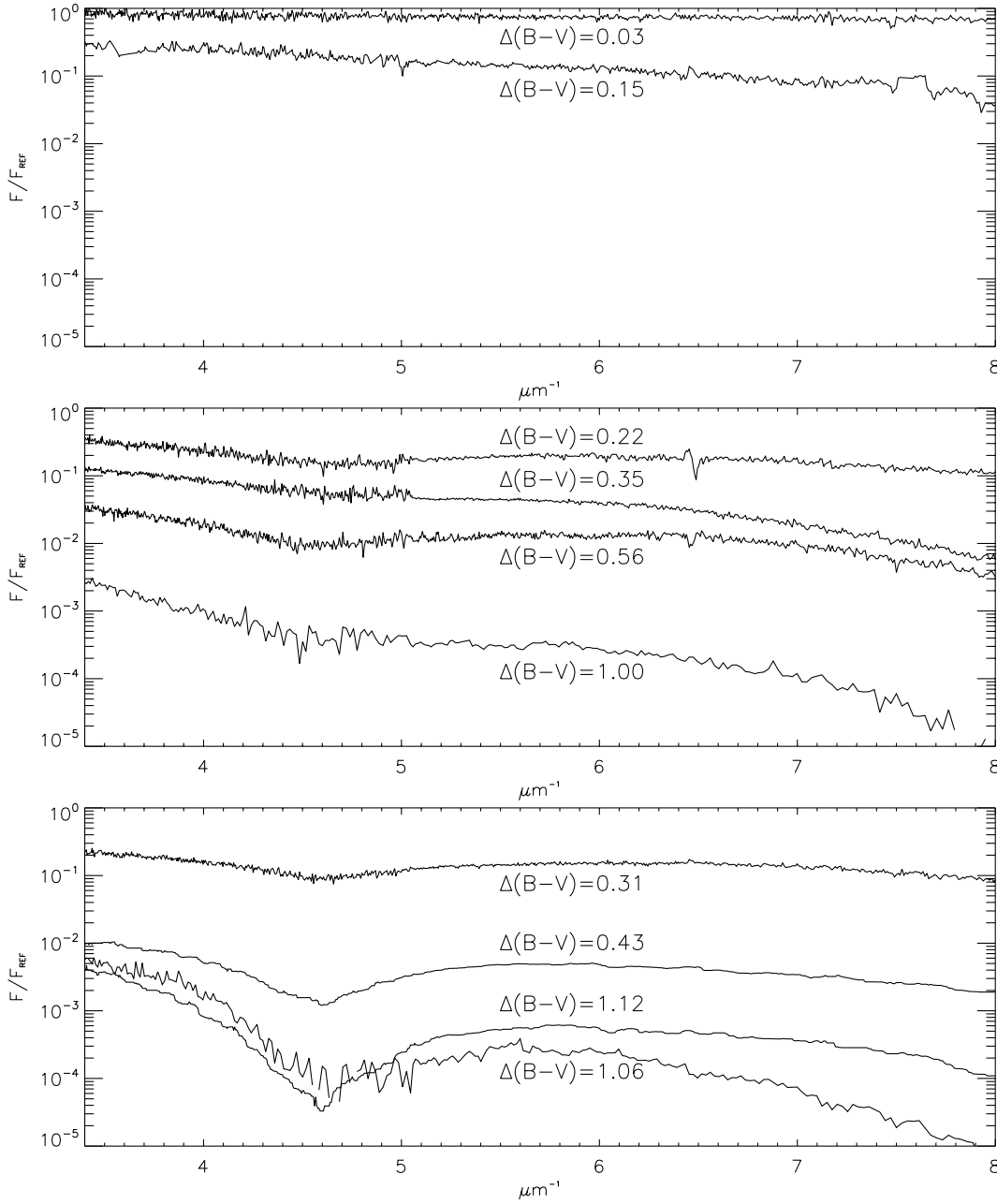


Fig. 1.— The three types of observed interstellar extinction curves: traditional bump-like extinction curves (bottom plot), extinction curves that deviate from linearity in the far-ultraviolet only (after the bump region, middle plot), linear over the whole visible/ultraviolet spectrum extinction curves (top plot). Each spectrum is the ratio of a reddened star to a reference star of low reddening, of the same spectral type. The spectra were approximately normalized using the reddening difference $\Delta(B - V)$ between reddened and reference stars and the Turner & al. (2014) extinction law for interstellar dust. Any extinction curve, in the Galaxy or in the Magellanic Clouds, falls into one of the three categories. It is clear from the figure that (i) $E(B - V)$ alone is not enough to fix the shape of an extinction curve, (ii) bump and linearity anti-correlate.

that extinction curves depend on different types of particles, which, as seen above, requires six (instead of one) independent parameters in addition to $E(B - V)$.

A second difficulty arising from the CCM paper is the assumption that R_V is the free parameter of interstellar extinction: a simple derivation from the fit proves that, in the CCM framework, R_V must be a constant ($=1.46$, Zagury (2012)). R_V cannot be variable as supposed by CCM, and constant as implied by the fit. This antinomy reflects the empirical nature of the CCM fit and the impossibility for R_V to be the free parameter of interstellar extinction: since interstellar extinction depends upon a single parameter (in addition to $E(B - V)$), and if R_V is not related to this parameter, R_V must stay constant (independent of direction, Zagury (2012); Zagury & Turner (2012)).

The CCM fit is also not always accurate (fig. 4 in CCM), especially in the 2200 Å bump region, because the fit establishes a one to one correspondence between the bump and reddening (no bump means $E(B - V) = 0$ and no extinction, and vice versa). The fit thus samples one category of extinction curves only, the curves with a bump (bottom plot of Fig. 1). It ignores the linear and linear down to the bump region extinction curves of Fig. 1, and is in manifest contradiction to the fact, already known in 1989, that the size of the bump is tied to $E(B - V)$ but does not depend exclusively on it (Savage 1975; Meyer & Savage 1981).

An improved, still one parameter dependent fit advantageously replaces the CCM parametrization for bump-like and linear over the whole spectrum (visible to far-ultraviolet) extinction curves (Zagury 2007). The fit shows that most extinction curves can be separated into a linear and a bump-like components. This breaks the univocal dependence of the bump on $E(B - V)$ of the CCM fit, does not increase the number of free parameters, and proves that normalization of extinction curves, as it is currently done in most studies, is not a straightforward process and another reason for the inaccuracy of the CCM fit. Like the CCM fit, the new fit lacks physical meaning. However, it matches all observations with much greater precision, and applies to nearly all extinction curves except for the minority of intermediate ones (middle plot of Fig. 1).

6. The incompatibility between the CCM and Fitzpatrick & Massa perspectives

The CCM and the Fitzpatrick & Massa fits proceed from two much different approaches. The latter relies on an assumption about interstellar extinction, the former on an empirical analysis of observations. The conclusions they reach are opposite and incompatible.

Assuming that interstellar extinction is the superposition of three different extinctions, Fitzpatrick & Massa conclude that reddening and six independent (unrelated) parameters are necessary to account for the variety of observed extinction curves. On the other hand, CCM and Bondar et al. (2006) consider extinction curves as a set of mathematical functions and search for the minimal dependencies of the curves. The CCM conclusion is unequivocal:

...the entire mean extinction law, from the near-IR through the optical and IUE-accessible ultraviolet, can be well represented by a mean relationship which depends upon a single parameter... the deviations of the observations from the mean relation are impressively small.

Few sight lines (7% out of 417 in Valencic et al. (2004)) escape the CCM relationship, exceptions being most certainly related to its purely empirical nature (Zagury (2007) and Sect. 5).

A recent textbook (Draine 2011) attempts to reconcile the opposing views of CCM and Fitzpatrick & Massa. The author suggests that CCM begun with a seven parameter fit F_{CCM}^7 ultimately transformed into a one parameter F_{CCM}^1 fit, once each of the parameters has been expressed as a function of R_V .

The Draine (2011) account of the CCM article is confusing and inexact. There is no mention whatsoever in CCM of a seven (independent) parameters fit of extinction curves. No expression of the Fitzpatrick & Massa parameters as a function of the CCM parameter was ever found by CCM, or anyone else. It would imply a dependency between the Fitzpatrick & Massa parameters that does not exist: the Fitzpatrick & Massa parameters have no relation between them, and no relation to the free parameter of CCM. Moreover, the R_V parameter,

which CCM adopt as the free parameter of interstellar extinction, is usually taken to be constant in the Fitzpatrick & Massa fit. These contradictions only attest to the discrepancies between the Fitzpatrick & Massa and the CCM fits, and to the antagonism between the Fitzpatrick & Massa assumption and observation, upon which the CCM finding relies.

Attempts to fit a large sample of extinction curves with physically meaningful particles, like the PAHs, requires a much larger number of free parameters than anticipated by observation, 226 (enough to sample the whole visible/ultraviolet spectrum) in a recent ApJ paper (Mulas et al. 2013). Although the authors concede that the number of free parameters must eventually be reduced from 226 to one, it is permitted to doubt that the goal be attainable at all.

7. Scattered starlight in the spectrum of reddened stars

The previous sections have shown that several logical deductions can be drawn from interstellar extinction observations. Interpretations of interstellar extinction curves based on the paradigm that we observe the extinction of the direct light from stars will hardly comply with these conclusions. Standard three components models for interstellar extinction face the following difficulties:

- a three component model is incompatible with the dependency of extinction curves on reddening and an additional parameter alone.
- the free parameter (in addition to $E(B - V)$) of interstellar extinction cannot be R_V , which must be a constant.
- the non-linearity of an extinction curve is intimately linked to the presence of the 2200 Å bump and vice versa. In other words, when (and only when) there is no bump, interstellar dust tends to recover a linear extinction law over the whole spectrum.
- the cross-section of interstellar dust in nebulae does not have the near-ultraviolet break predicted by three component models: the extinction law found in nebulae is continuous

and linear over the whole spectrum (Zagury 2000a, and next section).

In addition, the bump tends to disappear (and the extinction curve becomes linear) at very low reddening and with the proximity of the star to the obscuring cloud.

Besides reddening, the only parameter that is seen to impact the shape of an extinction curve is the distance between the star and the interstellar matter on the line of sight, a conclusion that does not make sense if extinction is the only process at work. This conclusion does make sense if, and this is the sole alternative to standard explanations of interstellar extinction, what is observed is not only the direct light from the reddened stars, but also comprises a non-negligible amount of scattered starlight.

8. What type of scattering?

Two types of scattering are commonly found in nature. One is scattering by particles with dimensions comparable to the wavelength. It is observed to vary as $1/\lambda^p$, with p of order 1, and is strongly forward oriented. Scattering by aerosols is the obvious example. The other case involves tiny particles, typically atoms or molecules, small compared to the wavelength. The scattering is then of Rayleigh type. It varies as $1/\lambda^4$ (a $1/\lambda^6$ term may also need to be considered (Dalgarno & Williams 1962)) and is nearly isotropic. Rayleigh extinction (and scattering) is by far less efficient than dust extinction.

IUE ultraviolet observations of nebulae prove that light scattered by nebulae in near-forward directions behaves as $1/\lambda^p$ ($p \sim 1$) (Zagury 2000a). The scattering can safely be attributed to interstellar dust grains and suggests that their linear extinction law at visible wavelengths extends in the ultraviolet. This result is not compatible with standard extinction models, which all suppose a modification of the size distribution of interstellar grains and a flattening of interstellar dust's extinction law at ultraviolet wavelengths. These observations show no trace of Rayleigh scattering.

However, there is no way to decompose an extinction curve into the sum of a component of direct starlight ($\propto e^{-a/\lambda^p}$, $p \sim 1$) and a component of light scattered by large grains ($\propto 1/\lambda^p e^{-a/\lambda^p}$, $p \sim 1$). Forward scattering by large grains in the

ultraviolet cannot explain the contamination by scattered starlight of the light received from reddened stars.

The analysis of a complete extinction curve F/F_0 of star HD46223, re-constructed from the near-infrared to the far-ultraviolet, shows that the spectral signature of its scattered light component varies as $1/\lambda^p$, with $p \sim 4$ (Zagury 2001a). The finding can be generalized to other directions (Sect. 10.2 and Zagury (2002)). The scattering is of Rayleigh type, due to gas on the line of sight. Fig. 2 plots the ratio f_s (dashed line) of scattered to direct light intensities found for HD46223.

There is a dilemma in observing a significant amount of scattered light by gas in the complete forward direction and being dominated by dust scattering as close as a few arc seconds from the star, while Rayleigh scattering is nearly isotropic and dust scattering strongly forward oriented. This dilemma can be solved only if the scattering by gas is, in the forward direction, coherent. In this case, the irradiance at the position of the observer should no more be in proportion of the number of scatterers on the line of sight, N_X , but of its square, N_X^2 . Compared to incoherent scattering, the irradiance is enhanced by a factor N_H (or N_{H_2}), that is by 10^{20} to 10^{22} (average column densities for HI and H_2 as given in table 1 of Friedman et al. (2011)).

9. Amount of scattered starlight

The magnitude of the scattered light component in the ultraviolet can be estimated by the gap between the observed extinction curve and the continuation of the linear extinction law at visible wavelength. Practically it should be given by the depth of the 2200 Å bump.

The scattered light intensity estimated for HD46223 (Fig. 2) is, in proportion of the direct light from the star corrected for reddening, of order $0.015/\lambda_\mu^4$ (λ in μm)². In the near-infrared scattered starlight is 2% of the (unreddened) star flux. The ratio grows to 16% in the V band, to 30% in the B-band, and scattered starlight becomes several times higher than the unreddened star's flux

²this estimation of the proportion of scattered starlight was derived assuming a $1/\lambda$ extinction law for interstellar dust. If the exact law is closer to $1/\lambda^p$, with $p > 1$, the proportion of scattered light should be larger.

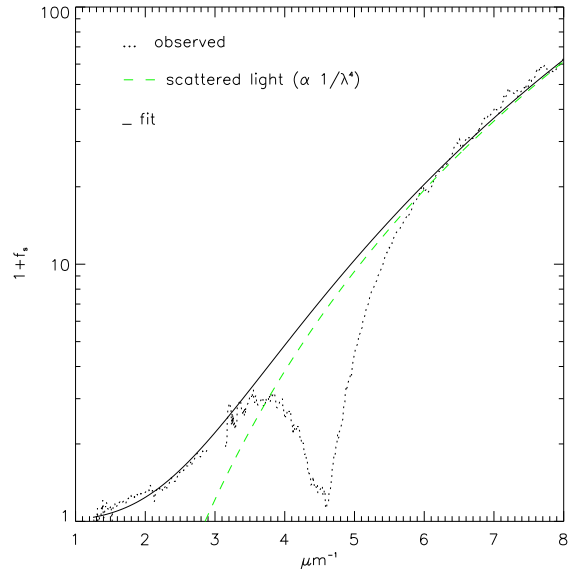


Fig. 2.— Ratio f_s of scattered to direct starlight for HD46223. The extinction curve of HD46223, after it has been corrected for the exponential extinction by dust, is in dots. It is fitted by the solid black line ($1 + a/\lambda^4$, $a \sim 0.015$ if λ is expressed in μm). The green dashed line is the continuum of scattered starlight, $f_s = a/\lambda^4$.

in the far-ultraviolet. The scattering component can be much larger than direct starlight would be without hydrogen on the line of sight.

10. Consistency

10.1. The value of R_V

R_V is a measure of the relative strength of the extinction by large grains in the B and V bands ($\tau_B/\tau_V = 1 + 1/R_V$), and an indicator of the size distribution of interstellar dust (see Zagury & Turner (2012)). It was recognized as a key parameter for interstellar dust in the 1960s (Zagury 2012). Whether it is a constant or varies has been a long standing debate between observers. In the wake of the CCM paper R_V was supposed to be variable, and the free parameter of interstellar extinction, by a large number of studies. On the opposite, users of the Fitzpatrick & Massa parametrization have usually adopted a constant $R_V = 3.1$ (Schlafly et al. 2010).

The exact ratio of absolute to selective extinc-

tion by interstellar grains is unlikely to be the free parameter of interstellar extinction (Sect. 5) and likely a constant, R_V^0 . Observed R_V values may differ from R_V^0 because of the presence of scattered starlight, which leads to underestimate A_V , and A_B even more (the scattering is stronger in the B-band). The exponent $p \sim 1$ for the extinction of the direct starlight is smaller than that for the scattered starlight ($p \sim 4$), which implies that observations underestimate the exact A_B/A_V ratios. Since $R_V = 1/(A_B/A_V - 1)$, observed R_V -values should overestimate R_V^0 . These consequences have also been illustrated in the Zagury (2001a) case study of HD46223's extinction spectrum.

Turner & al. (2014) did find a minimum, $R_V^0 = 2.82$, in observed values of R_V . The corresponding extinction law $\tau_\lambda \propto 1/\lambda^{1.37}$ ($F/F_{ref} \propto e^{-1.14E(B-V)/\lambda^{1.37}}$) agrees with near-infrared observations (fig. 2 in Zagury & Turner (2012)). Incidentally, it also coincides with atmospheric aerosols observations.

10.2. Agreement with observation

The true extinction law of interstellar matter should be quasi-linear over the whole visible to ultraviolet wavelength range, presumably with the same exponent p in the visual and ultraviolet spectral domains. A second additive component of scattered starlight (due to H or H₂ on the line of sight) explains the departure from linearity of observed extinction curves.

Scattered starlight diminishes the impression of reddening and explains why the departure from linearity in either the visible wavelength range (Nandy 1964) or in the far-ultraviolet (middle plot of Fig. 1) is always perceived as less extinction. When reddening is very low, scattering is very low, and the linear extinction law of interstellar dust can be appreciated over the whole spectrum. When reddening increases, scattering increases as well, and divergence from linearity appears, predominantly in the ultraviolet, as observed. If the star is close to the scattering material, coherence is diminished or lost (Sect. 11.3): the linearity at visible wavelengths of the extinction curve tends to be continued in the ultraviolet domain, which is also what is observed.

The shape of an observed interstellar extinction curve is fixed by two parameters, the reddening

$E(B-V)$ and a free parameter which regulates the proportion of direct and scattered starlight (thus the size of the 2200 Å bump, Sect. 3). This parameter is related to distances between the star, the interstellar cloud, and the observer, in a way that remains to be determined.

Extinction in the Magellanic Clouds, or in other galaxies, needs not to be considered as singular. Linear extinction curves exist in the Galaxy. Magellanic Clouds sight-lines sample both local (Magellanic) clouds, infinitely close to the stars with respect to the observer, and Galactic cirrus, for which Magellanic stars are infinitely far away. The coincidence of these two extreme situations along the same lines of sight is the only singularity of Magellanic extinction curves. It must, along with the relatively low column densities of the Galactic cirrus on the line of sight, explain why the curves tend to be linear at higher reddening than along standard Galactic sight-lines, and accordingly have reduced 2200 Å bump and DIBs (Sect. 12).

The $1/\lambda^4$ dependence of the scattered starlight component of extinction curves can be verified over a large sample of stars (Zagury 2002). After multiplication by λ^4 , the far-ultraviolet spectrum of an extinction curve with a bump will generally be found to be an exponential with an exponent close to the one deduced from the visual extinction. The exact amount of dust extinction at visible wavelengths can thus be retrieved from the far-ultraviolet spectrum of a reddened star, and the relationship between visual and far-ultraviolet extinctions, empirically highlighted by CCM and Bondar et al. (2006), finds its physical meaning. Reddening $E(B-V)$ obtained from the far-ultraviolet spectrum should be larger than the value observed in the visible wavelength range, the latter being slightly diminished because of the scattered starlight contribution.

11. Observation and theory

11.1. Van de Hulst formula

In Section 4.3 of his book van de Hulst considers the scattering of an incoming plane-wave by a slab of identical, spherically symmetric particles, and sums, for the forward direction, the contributions of the scattered waves to the disturbance at the position of a far-away observer. Van the

Hulst assumes that the particles are separated by distances larger than the wavelength ($n_X \lambda^3 \ll 1$, with n_X the density of the particles).

Van de Hulst's formula leads (Zagury & Pellat-Finet 2012) to a ratio between the scattered and the un-reddened (without the slab of particles on the line of sight) irradiances at the observer position

$$\frac{I_s}{I_0} = \left(\frac{4\pi^2 \alpha_X N_X}{\lambda} \right)^2 = \frac{3}{8\pi} N_X^2 \lambda^2 \sigma_X \quad (1)$$

N_X is the column density of the particles, $\alpha_X \sim \frac{9}{2}a^3$ their polarizability, a their mean size. Cross section σ_X is related to the polarizability by $\sigma_X = \frac{8}{3}\pi k^4 \alpha_X^2$ (Van de Hulst 1981, sect. 6.11). For molecular hydrogen the cross section comprises terms in k^6 and k^8 which have, in the ultraviolet, the same weight as the k^4 term (Dalgarno & Williams 1962). Eq. 1 anticipates a $1/\lambda^2$ dependence for the irradiance of the scattered light if atomic hydrogen is the scatterer, with possible higher powers of $1/\lambda^2$, if it is H_2 .

For directions with $E(B - V)$ between 0.1 and 1, which are the directions where a bump at 2200 Å is most commonly observed, N_H is between 10^{21} and $5 \cdot 10^{22} \text{ cm}^{-2}$ and N_{H_2} typically an order of magnitude less (Table 1 in Friedman et al. (2011)). Condition $n_X \lambda^3 \ll 1$ is doubtless verified since densities should range from a few ten particles (HI clouds) to a few hundred particles per cm^3 (molecular clouds) (Draine 2011). For $\lambda = 1500 \text{ Å} = 1.5 \cdot 10^{-5} \text{ cm}$, $\sigma_H = 1.2 \cdot 10^{-25} \text{ cm}^2$ and $\sigma_{H_2} = 3.4 \cdot 10^{-25} \text{ cm}^2$, I_s/I_0 anticipated by Eq. 1 is in the range $10^5 - 10^6$.

11.2. Theoretical irradiance against measured power

A plane of oscillators creates a disturbance at an observer position that is fixed by the oscillator strength per unit area (Apps. A.1 and A.1.2). A region scaling with the first Fresnel zone contributes most to the disturbance.

The oscillator strength per unit area of the interstellar particles responsible for the scattered component of extinction curves is $(2\pi/\lambda)^2 \alpha_X N_X$ (Van de Hulst 1981; Zagury & Pellat-Finet 2012). It is $1/\lambda$ for a Huygens-Fresnel wavefront (App. A.1.2). The ratio of the two quantities should give the disturbance of the interstellar

dipoles relative to Fresnel's hypothetic molecules, which is what van de Hulst's formula, Eq. 1 for the irradiance, expresses.

The formula contains no information on distances. This is predictable since scattering from a first Fresnel zone is independent of the position of the zone between the source and the observer (Sect. A.1.2).

A refined representation of the interstellar cloud, which would also satisfy van de Hulst's (unjustified in the textbook) requirement of mutual distance between the particles larger than the wavelength, would be that of a succession of wavefronts (instead of a single one) along the line of sight, all excited by the same plane wave. Each wavefront removes a very small fraction of the source energy and the scattered waves from all wavefronts arrive with the same phase at the observer position. The expression of the irradiance (Eq. 1), however, should not be modified³. A further simplification of interest would be to limit the cloud to the first Fresnel zones of the wavefronts (for a star far away, a cylinder of radius $\sqrt{\lambda L}$ and depth $e = N_X/n_X$ seen edge on).

These representations underline a similarity with Fresnel zone plates (App. A.2), with the contributing areas aligned along the line of sight instead of being in an orthogonal plane. Zone plate theory shows that the contribution of coherent sources at a focus may considerably enhance the irradiance, like the square of their number, without prejudicing energy conservation. For the far-field, the increase of the irradiance is balanced by the focalization of the scattered wave along the direction of the source. The power measured at the focus must remain a limited proportion of the power available for coherent scattering.

³with N identical wavefronts, the surface density of each wavefront is $w = N_X/N$ ($w\lambda^2 \leq 1$) and the irradiance due to a single wavefront $1/4$ the irradiance due to the first Fresnel zone, $(wS_\lambda)^2 \alpha_X^2 I_0$. The irradiance for the whole set of wavefronts in the forward direction is $N^2(wS_\lambda)^2 \alpha_X^2 I_0/4 = (N_X S_\lambda)^2 \alpha_X^2 I_0/4$, as in Eq. 1. As long as the thickness e of the cloud remains small compared to the star-cloud and observer-cloud distances, the phase difference at distance q from the star-observer axis does not vary much between the front and back edges of the cloud: there should be no major difference considering the cloud as a succession of Fresnel zones or as a single one.

11.3. Qualitative discussion of the interstellar extinction problem

For a star infinitely far away, the region of the interstellar cloud that should contribute most to the scattered starlight at the observer position corresponds to an area of order λL . This area is subtended by a very small angle ($\sim \sqrt{\lambda/L}$), by far smaller than the resolution a telescope can reach. Varying the size of the telescope will not modify the proportion of scattered starlight.

As for zone plates, the power measured by the telescope should also be found to be in proportion to the light extinguished within the area of coherence and increase as N_X (instead of N_X^2), thus in proportion to $E(B - V)$ and to the size of the Fresnel zone ($\pi\lambda L$) as seen by the observer. The variations of the average ratio of the size of the 2200 Å bump to $E(B - V)$, which differs from one Galactic region to another (Meyer & Savage 1981; Massa & Fitzpatrick 1986), must result from the different distances of these regions from the sun (and not from variations of interstellar dust composition in different Galactic regions). Deviations from the mean ratio within a Galactic region, on the other hand, are more likely due to variations of star distances, or to an additional extinction (e.g. circumstellar extinction) on the line of sight.

In specific directions, when the size of the first Fresnel zone shrinks due to the proximity of the star, the power available for coherent scattering, the proportion of scattered light in the spectrum the reddened star, and the 2200 Å bump, diminish.

A star may be comparatively close to the interstellar cloud and yet yield large Fresnel zones, meaning that distance star-cloud D is large but that the cloud is much closer to the star than to observer ($D \ll L$), as it occurs for Magellanic stars extinguished by local (Magellanic) clouds. The area of the first Fresnel zone, now of order λD , is then small compared to λL and fixed by the proximity of the star instead of the observer-cloud distance.

Magellanic stars also have low column density Galactic cirrus (for which the stars are infinitely far away) on the line of sight. That DIBs are observed at the Magellanic Clouds redshift (Sect. 12), indicates that the 2200 Å bump and the scattered starlight component of Magellanic extinction curves should be attributed to Magel-

lanic interstellar clouds rather than to Galactic cirrus. Then, the reason why bumps and DIBs are weaker in observations of Magellanic stars is that Galactic cirrus on the line of sight are too light to give appreciable scattered starlight. This would imply a symmetry of the roles played by the observer and the star in the determination of the amount of scattered starlight, and suggest that the free parameter of interstellar extinction curves is the size of the first Fresnel zone.

Quantitatively there is no straightforward way that I know of to move from the irradiance given by Eq. 1 to the power of the scattered starlight that a telescope will measure. The parallel initiated in this paper between Fresnel and interstellar oscillators, between the forward scattering by identical dipoles and wave theory, can probably be pushed further. Abnormally large Fresnel zones, as one finds on astronomical scales, address a problem to wave theory, the solution of which should help the analytical treatment of interstellar extinction curves.

12. Connection between the diffuse interstellar bands and the 2200 Å bump

The facts that the 2200 Å bump and the DIBs concern different wavelength domains and that the bump is a far more prominent feature, may justify that the bump and the DIBs are most often treated independently. For instance, the bump is not mentioned in the Herbig (1995) review on the DIBs.

Benvenuti & Porceddu (1989), although from a limited sample of 26 stars, concluded that the bump and the DIBs, apart from a common tendency to increase with reddening, do not correlate. On the other hand, Nandy & Thompson (1975); Wu et al. (1981), from larger studies of 60 and 110 stars, find a strong correlation between the equivalent widths of the bump and of the large DIB $\lambda 4430$.

There is no general strict proportionality between the DIBs and the bump, but no such exact proportionality between the DIBs exists either (Krelowski & Walker 1987; Herbig 1995; Xiang et al. 2012). However, as the Friedman et al. (2011) article points out, when the DIBs are observed, the bump is observed, and vice versa; and when one is substantially weakened, the other is weak-

ened as well. This is true for the Galaxy as well as for the Magellanic Clouds.

In the Magellanic Clouds Welty et al. (2006); Welty (2014) find that DIBs are, like the 2200 Å bump, typically weaker for LMC and SMC directions than for Galactic sight lines with similar HI column density, by factors of 9 and 20 respectively. Cox et al. (2007) note that the presence or absence of DIBs in the Magellanic Clouds is linked to the presence or absence of a 2200 Å bump.

In the Galaxy, there are a few well known sight-lines with anomalously weak DIBs: in Orion, stars HD36822 ($E(B - V) \sim 0.14$), HD37020 (0.37), HD37021 (0.54), HD37022 (0.34), HD37042 (0.42), HD37061 (0.52); HD147933 (ρ -Oph, 0.45); HD24534 (χ Per, 0.56); HD29647 (1); HD34078 (AE Aur, 0.52); HD57061 (τ CMa, $E(B - V) \sim 0.16$); HD62542 (0.35); HD148184 (0.5); HD223385 (6 Cas, 0.67); Herschel 36 (0.87) (Welty 2014; Dahlstrom et al. 2013; Friedman et al. 2011; Moutou et al. 1999; Snow 2002).

In all of these directions the 2200 Å bump is significantly weaker than expected from the reddening. The ultraviolet extinction curves of Herschel 36 in NGC 6530 and HD29647 in Taurus are remarkable because of the high reddening in these directions and a nearly absent 2200 Å bump (Snow & Seab 1980; Dahlstrom et al. 2013). The curves are of the intermediate type (middle plot) of Fig. 1; the weakness of the bump in these curves coincides with the extension of the linear extinction law at visible wavelength down to the bump region.

A relationship between the DIBs and the distance from the star to the reddening material has also been found for Galactic stars. Morgan (1944) associates a "systematically weakened" DIB $\lambda 4430$ to nebular material in the vicinity of stars. The tendency for DIB $\lambda 4430$ to increase with star distance also appears on a plot (fig. 6 in Duke (1951)) of the DIB's strength versus distance moduli for a sample of stars with similar reddening. From a survey of bibliographical sources Snow et al. (1995) concluded that

The general trust of this literature is that the bands [DIBs] are either weak or absent in circumstellar regions of all descriptions, including both hot star and cool star envelopes.

The Galactic stars with weak DIBs mentioned

above are generally bright in the far infrared which is an additional proof that part of the reddening material on the line of sight is close to the star. AE Aur, ρ -Oph, CMa, are known to be close to or embedded in nebulae (Vos et al. 2011; Van den Berg 1966). The study by Dahlstrom et al. (2013) on Herschel 36 separates a foreground ($E(B - V) \sim 0.38$) and a local ($E(B - V) \sim 0.49$) extinction with comparable weights in the total reddening of the star.

The diffuse interstellar bands and the 2200 Å bump are concomitant in the spectrum of reddened stars and share the same properties: they globally increase with the amount of interstellar material, do not depend on the reddening alone, and tend to disappear when interstellar matter is close to the star. At very low reddening (typically less than 0.08 mag.) neither the bump nor the DIBs are observed.

13. H₂ absorption lines and the Diffuse Interstellar Bands

Draine's recent comment that "it is embarrassing to have to admit that not a single one [DIB] has yet been identified" (Draine 2009) is only partially exact. A large number of DIBs can be associated to H₂ absorption lines, but no convincing mechanism for these absorptions has been proposed, which has discredited the hypothesis.

In the 1970s, J.A. Duaro (Duardo 1970, 1971, 1974, 1975) first noted that several DIBs match H₂ inter-Rydberg transitions from electronically excited states of H₂. The finding was independently developed by P. Sorokin and J. Glowina (Sorokin & Glowina 2000; Sorokin 2013).

Laboratory experiments did reveal an absorption spectrum of H₂ having "topological resemblance with observed DIB profiles" (Hinnen & Ubachs 1996), and coincidences between DIBs and H₂ resonances from ground state levels populated at low temperatures (Ubachs et al. 1997; Ubachs 2014).

The Sorokin & Glowina model supposes a two-photon absorption of coherent light mechanism:

.. a mechanism based entirely upon "passive" two-photon absorption by H₂ molecules cannot adequately explain the origin of the DIBs. As will

be explained below, we currently assume that some form of coherent light wave structure is present in the H₂-containing cloud... (Sorokin et al. 1998).

Two photon absorptions

normally occur with high probability in any medium only if the latter is simultaneously irradiated by intense, ideally monochromatic, light - such as that produced by a laser. (Sorokin & Glowina 2006).

Sorokin & Glowina were led to the conclusion that the DIBs, and the bump, are produced in the vicinity of O and B stars⁴. As Snow (1995, 1998) already pointed out, this is untenable with respect of the observed properties of the bump and of the DIBs (previous section).

That the Sorokin & Glowina mechanism cannot be retained should not disqualify the whole model, especially because of the striking coincidence between several DIBs and H₂ -the most abundant molecule in interstellar clouds- absorption lines, and because no other molecule has yet been found that would provide such a large number of DIB identifications.

With an energy centered close to 5.7 eV the bump lays about half the energy needed to photodissociate molecular hydrogen (Draine 2011, p. 419). A two photon absorption, favored by the coherence (as required by the Sorokin & Glowina hypothesis) of the scattered light along the star-observer direction, could explain the bump, leave unaffected the direct light from the star, and provide the H₂ excited state needed for DIB absorptions. Major difficulties would nevertheless remain in finding the exact selection rules, especially that the ground state of hydrogen is gerade while the first gerade excited state to be reached in a two photon absorption, is, according to Ross & Jungen (1994), at 12.29 eV.

⁴"this famous absorption feature [the 2200 Å bump] is not formed in deep interstellar space far away from any stars, as astronomers have generally assumed over the years, but rather originates in the gaseous clouds (containing mostly H₂) that often closely surround bright and massive OB stars." Sorokin (2013).

14. Miscellaneous

14.1. Star distances

Scattered starlight in the spectrum of reddened stars affects cosmic distances estimations because apparent magnitudes are overestimated. A bias also arises from the fact that standard extinction models tend to underestimate the extinction.

On the one hand, the presence of scattered starlight means that a fair amount of light is introduced into the beam of observation, from directions other than the direction of the reddened star. The star appears brighter than it truly is, its observed apparent V-magnitude m_V is less than what it should be (m_V^0) without the scattered starlight. Neglecting the distinction between m_V and m_V^0 , the star's moduli is underestimated, which implies an underestimation of star distances.

On the other hand, standard extinction models do not acknowledge the presence of scattered starlight in the spectrum of reddened stars, and, instead, assume a smaller extinction than there really is. Visual reddening A_V and color index $E(B - V)$ are underestimated, while the absolute to relative extinction parameter R_V is overestimated (Sect. 10.1). The more scattered starlight in the spectrum of a reddened star the larger should be the overestimation of R_V ⁵.

An underestimation of the extinction unavoidably leads to overestimated distances. This was well pointed out by the Russell & Shapley (1914) investigation, conducted at a time (the 1910s) when whether or not interstellar extinction existed was becoming a key issue for models of the universe. The paper shows that a mean extinction of 0.019 mag. per 10 pc in the V band cuts distances by two for stars predicted to be 4 kpc away under the assumption of no reddening (the stars are 2 kpc away with an extinction of $A_V \sim 1$ mag.).

A component of scattered starlight in the spectrum of reddened stars or a deficiency of extinction should the scattered starlight be ignored, both describe the same observation, that is, the gap be-

⁵Remarkably enough, the recent Schlafly et al. (2016) article does find a global increase of R_V as interstellar clouds get farther away from the Sun, that perfectly matches the ideas introduced in this paper, while being extremely difficult to accommodate with traditional extinction models.

tween observed extinction curves and the extension of the linear visible extinction towards the ultraviolet. Therefore, if A_V^0 is the exact visual extinction, and with the notations defined above: $A_V - A_V^0 = m_V - m_V^0$.

The exact distance moduli for a reddened star of absolute V magnitude M_V is

$$m_V^0 - M_V = 5 \log(d/10\text{pc}) + A_V^0, \quad (2)$$

which can be rewritten as

$$\begin{aligned} m_V - M_V &= 5 \log(d/10\text{pc}) + A_V^0 + (m_V - m_V^0) \\ &= 5 \log(d/10\text{pc}) + A_V \end{aligned} \quad (3)$$

Eqs. 2 and 3 are different expressions of the distance moduli but lead to the same value for distance d , provided that A_V ($\neq A_V^0$) be correctly estimated. Traditional extinction models use empirical methods for the determination of either A_V (Balázs et al. 2004; Cardelli, Clayton, & Mathis 1989), or R_V (Schlafly et al. 2016), with impressively large error bars (Turner 2012), and distances which can vary by a factor of two.

Standard extinction models do not introduce any specific error on distances but the more scattered starlight there is, the more models need to increase R_V ($\neq R_V^0$, which is a constant). R_V can easily be underestimated, for instance if a canonical value $R_V \sim 3$ is applied. Eq. 3 shows that the relative error $\Delta d/d$ is of order $E(B - V)\Delta R_V/5$. An underestimation of R_V within standard frameworks can lead to an overestimation of distances up to a few 10%.

14.2. The PAH hypothesis

Poly-Aromatic-Hydrogenated molecules (PAHs) are part of nearly all three components models for interstellar extinction. Introduced in the 1980s to explain the infrared Unidentified Bands (UIBs, Leger & Puget (1984)), PAHs have soon been proposed to palliate most of un-understood features of interstellar extinction, over the whole spectrum.

PAHs have been supposed to be the carriers of the far-ultraviolet rise of extinction curves (Désert, Boulanger, & Puget 1990), of the 2200 Å bump (Steglich & al. 2010; Draine 2009), of the DIBs (Duley 2006). They have also been thought to be the source of the Red Rectangle spectral features (Witt et al. 2009), and, according to Gordon et al.

(1998), would be responsible for some 50% of the Galactic red light.

PAHs probably have little to do with the continuum of ultraviolet extinction and with the 2200 Å bump (this paper), their contribution to the DIBs is disputable (Sorokin et al. 1998; Ubachs 2014; Tielens 2008), and they certainly do not contribute to the red light of Galactic cirrus (Juvela et al. 2008; Zagury et al. 1999), *a fortiori* not to the diffuse Galactic light (Zagury 2006). In addition, should they exist with the required properties, the observed fractional abundance of neutral PAHs would be $\sim 10^{-9}$ less than hydrogen (Gredel et al. 2011), which is extremely low, certainly much lower than what models anticipate⁶.

As a recent 2012 meeting ("The PAH Hypothesis") recalls, PAHs remain, despite large theoretical and laboratory efforts to match their chemistry to interstellar issues, hypothetical constituents of the interstellar medium. The existence of PAH molecules having the properties recalled above can legitimately be questioned.

15. Conclusion

If we do see the direct light from the stars extinguished by interstellar particles, a minimum of three different types of particles, acting independently one from the other, are necessary to explain the observed visible-ultraviolet interstellar extinction spectrum. There are logical incompatibilities between this assumption and observation. The sole alternative is that scattered starlight is mixed with the direct light we receive from reddened stars and substantially modifies their extinction spectrum. In addition to the spectrum of a reddened star, the observer sees the first order diffraction pattern of hydrogen atoms or molecules in the cloud on the line of sight.

Fresnel's theory can be used to overcome most of the objections that the attribution of the ultraviolet non-linearity of extinction curves to a scattering process can raise. It provides the elementary ideas that explain the observed properties of the scattered light component in the spectrum of reddened stars, its magnitude, and the reason why it becomes appreciable only when distances

⁶the total abundance of neutral and ionized PAHs is supposed to be of order 10^{-7} , see Tielens (2008).

are extremely large. It also indicates that, besides column density, the key parameter of interstellar extinction is related to the size of the first Fresnel zone at the cloud position, as seen by the observer.

Diffraction from very large Fresnel zones still addresses a challenge to the theory, which does not provide a straightforward fit for interstellar extinction curves.

Over the years this alternative interpretation of the continuum of extinction curves has received several independent confirmations through the analysis of different types of observation: the ultraviolet spectrum of nebula, which does not indicate a discontinuity between the visible and the ultraviolet spectrum of the scattering cross-section of interstellar dust; the ultraviolet reddening law of stars with very little reddening, which is linear over the whole spectrum; the analysis of the relationship between the visible and far-ultraviolet extinctions; and the study of Magellanic extinction curves, which tends to prove the universality of the extinction law of interstellar matter.

Three implications are worth noting:

1. The three major features of interstellar extinction (the ultraviolet deviation of the continuum from linearity, the 2200 Å bump, and the diffuse interstellar bands) are intimately connected. They have the same properties (e.g. they cancel at very low reddening or when the interstellar matter is close to the reddened star) and are concomitant. The bump has the peculiarity of being a selective extinction of the scattered starlight component of extinction curves.
2. Three component models and the assumption that scattered starlight contaminates the spectrum of reddened stars, are two descriptions of the same phenomenon from viewpoints that are mathematically equivalent for distance estimations. Classical (no scattered starlight) derivations of cosmic distances underestimate the true extinction and need to overestimate the R_V parameter. The uncertainty on the R_V value to adopt for each direction can hamper the reliability of classical photometric distance derivations, more likely in the sense of an overestimation of cosmic distances. At intermediate distances (a few hundred parsecs) parallactic

distances should generally be favored when compared to photometric distances.

3. This review of interstellar extinction theory questions the basis of traditional interstellar dust models, i.e. the separation of extinction curves into three distinct wavelength domains, the justification of which has led to the search for hypothetic molecules, such as the PAHs. The existence (with the required properties) of these molecules is unnecessary and doubtful. It is quite common in the history of science to see the failure of a search for particles eventually justified by the fact that these particles do not exist. Fresnel's "molécules éthérées" is one example. This should be even more true for particles whose density should be 10^{-9} the density of H_2 (Gredel et al. 2011), in a medium, the interstellar medium, close to vacuum.

In this framework, hydrogen (atomic and/or molecular) is the major and probably unique agent of the remarkable properties of interstellar extinction. Item 1 implies that DIB research cannot be conducted independently from a more general reflection on the two other major features (the continuum and the bump) of interstellar extinction. Sect. 13 recalled that molecular hydrogen is the only molecule to which a large number of DIBs can be assigned, a fact that would be worth investigating more deeply. It was suggested in this paper that the 2200 Å bump was a two photon absorption by molecular hydrogen of coherent scattered starlight. From the excited state, molecular hydrogen absorption at the DIBs frequencies becomes possible.

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A. Diffraction theory as the basis of coherent forward Rayleigh scattering

Fresnel's theory, the first theory to account for diffraction phenomena, was also first to explain Fermat's principle of least time, and lies behind scattering theory. The basic idea supposes the existence of a medium of small oscillators ("molécules éthérées") which transmit the light vibration, preferentially in the forward direction. Light propagates through the excitation of the successive layers (wavefronts) of oscillators centered on the source of light. The specific nature of these oscillators and the characteristics of the medium were never clarified, for the good reason that they do not exist.

Modern presentations of wave theory rely on the estimate of the contribution of a small area δS of a wavefront to the irradiance at an observer's position, or focus, P . Area δS (at distance D from the source and l from the observer) needs to be neither too small (Sect. A.3), nor too large (to avoid appreciable phase-lags within δS), compared to the wavelength. The contribution $u_{\delta S}$ of δS to the disturbance U_0 at P is fixed by the size of the area (the number of oscillators is proportional to the area) and by the path-difference $\Delta_{\delta S}$ between the trajectory light follows from the source to the observer passing by δS , $D + l$, and the straight source-observer distance $D + L$.

Dismissing the $e^{i\omega t}$ time-dependence, the disturbance $u_{\delta S}$ consists in an amplitude and a phase-lag term. The amplitude, $\epsilon_\lambda A \delta S / (lD)$, is proportionate to the radiation field at the wavefront location ($A \delta S / D$) and propagates as the inverse-distance $1/l$ from δS to the observer. The proportionality coefficient ϵ_λ depends on the wavelength and stands for the strength per unit area and unit radiation field of Fresnel's oscillators in the forward direction.

The phase-lag term $e^{i\varphi_{\delta S}}$ of $u_{\delta S}$ differentiates the contributions of different areas according to their position on the wavefront. If r is the distance from δS to the source-observer axis

$$\Delta_{\delta S} = \frac{r^2}{2} \left(\frac{1}{D} + \frac{1}{L} \right) \quad (\text{A1})$$

$$\varphi_{\delta S} = \frac{2\pi}{\lambda} \Delta_{\delta S} = \pi r^2 \frac{D + L}{\lambda D L} \quad (\text{A2})$$

$$u_{\delta S} = \frac{A}{D} \frac{\epsilon_\lambda}{L} e^{i\varphi_{\delta S}} \delta S \quad (\text{A3})$$

The irradiance area δS alone would induce at P is in proportion of δS^2 although the power crossing the area is proportional to δS . Therefore, N identical neighboring areas with negligible phase differences at P contribute as $N^2 \delta S^2$ to the irradiance at P while the power crossing the areas increases as $N \delta S$. It implies a concentration of power at the focus, a depletion elsewhere, which underlie diffraction phenomena.

A.1. The first Fresnel zone

A.1.1. Definition

The first Fresnel zone is the disk centered on the direction of the source within which contributions of a wavefront cooperate constructively to the light received by the observer: light paths between the source and the observer passing through any two points within the zone differ by less than half the wavelength ($\varphi_{\delta S} < \pi$, $\Delta_{\delta S} < \lambda/2$). It is the area around the source-observer axis that gives the largest possible contribution to the irradiance at P . Successive Fresnel zones are defined by rings of constructive interferences (from positions within the ring) at the observer position.

At distance L from the observer and D from the source, the radius and area of the first Fresnel zone are

$$r_\lambda = \left(\lambda \frac{DL}{D + L} \right)^{0.5} \quad (\text{A4})$$

$$S_\lambda = \pi \lambda \frac{DL}{D + L} \quad (\text{A5})$$

For a given distance between the source and the observer, S_λ is small close to the source and close to the observer, and maximal ($S_\lambda = \pi\lambda L/2$) in-between. But the largest size a Fresnel zone can reach at a given distance from the focus is obtained for an incoming plane wave (the source is infinitely far away and the wavefront is a plane), $S_\lambda = \pi\lambda L$.

The order of magnitude for the radius of a first Fresnel zone is typically a few millimeter in laboratory experiments, 100 m within the solar system, 1000 km a few hundred parsecs away.

The Fresnel zone of order j is the region of the wavefront within which the phase shift is in-between $(j-1)\pi/2$ and $j\pi/2$. It is limited by the rings of radius r_j and r_{j+1} with

$$\begin{aligned} r_1 &= r_\lambda \\ r_j &= j^{0.5} r_\lambda \end{aligned} \quad (\text{A6})$$

All Fresnel zones have same area (πr_λ^2) but the thickness of the ring they delimit decreases quickly with increasing order of the zone.

A.1.2. Contribution of a first Fresnel zone to the irradiance

Should a first Fresnel zone be divided into N rings of equal area $\delta S = S_\lambda/N$, the phase-lag of ring j is $\varphi_j = j\pi/N$. The disturbance at P due to the first zone alone is (Eq. A3 and $N \gg 1$)

$$\begin{aligned} U_1 &= \sum_{j=0}^{N-1} u_j = \frac{A\epsilon_\lambda}{DL} \delta S \sum_0^{N-1} e^{i\varphi_j} \\ &= 2i\lambda \frac{A}{D+L} \epsilon_\lambda \end{aligned} \quad (\text{A7})$$

$$= 2i\lambda \epsilon_\lambda U_0, \quad (\text{A8})$$

since $\sum_0^{N-1} e^{i\varphi_j} = \frac{2i}{\pi} N$. Disturbance U_1 from a first Fresnel zone is independent of the position of the wavefront between the source and the observer and is, as expected, proportional to disturbance U_0 at P (the observer's position).

Fresnel argued that a limited part (characterized by the size of the first zone) of the wavefront around the source-observer axis contributes most to the irradiance at P since a small solid angle issued from the observer intercepts an increasingly large number of Fresnel zones as it is moved away from the direction of the source, and their contributions tend to cancel out on the average. In addition, the disturbance from any half of a Fresnel zone, except the first, is annihilated by the half from one of the two nearest zones.

According to Fresnel, disturbance U_0 at P should be the disturbance due to half the first zone alone, half the disturbance due to the whole first zone. The argument neglects the phase variations within a zone, but was eventually refined (Born 1999; Hecht 2003): the disturbance amplitude at P is in fact half the one the first zone alone would provoke and $1/\sqrt{2}$ times the disturbance due to half the first zone. The irradiance at P is 1/4 the irradiance due to the first Fresnel zone and half the irradiance due to half of the zone.

Equations (Eqs. A1 to A8) and most reasonings obtained so far apply to any set of identical dipoles, regardless of the particular case of light diffraction. The value of ϵ_λ is fixed by the nature of the oscillators.

For Fresnel oscillators one must have $U_1 = 2iU_0$ and therefore $\epsilon_\lambda = 1/\lambda$ with disturbance U_1 a quarter of a period out of phase with the source at P ,

$$U_1 = \frac{2Ai}{L+D} = 2iU_0 \quad (\text{A9})$$

$$u_{\delta S} = \frac{A}{\lambda LD} e^{i\varphi_{\delta S}} \delta S \quad (\text{A10})$$

Eq. A10 gives the irradiance per unit area in the forward direction, from which an irradiance for a unit area $i_0 = |u_{\delta S}/\delta S|^2$ can be defined. If N identical small areas cover the first Fresnel zone, the disturbance

they create at the observer position is the product of $(Nu_{\delta S})^2$ by a phase-lag term $(\frac{2}{\pi}N)^2$, and the following equalities relate the irradiance I_0 at P to the irradiance I_1 due to the first zone alone, to i_0

$$I_0 = 4I_1 = 4(2/\pi)^2 N^2 |u_{\delta S}|^2 = \frac{4}{\pi} \frac{S_\lambda^2}{\lambda^2} i_0 \quad (\text{A11})$$

The irradiance at P equals the irradiance due to any sub-set of the first zone with identical areas, as they had no phase lag at P , times $(2/\pi)^2$.

A remarkable property of first Fresnel zones is that their contribution to the disturbance (equally to the irradiance) at P depends neither on the size of the zone (its position between the source and the observer) nor on the wavelength.

The importance of first Fresnel zones was acknowledged by Van de Hulst in the following terms:

The amplitude at a distance l beyond a plane wave front is such as if an area λl of the wave front contributes with equal phase and the remaining part of the wave front not at all.....A pencil of light of length l can exist only if its width at its base is large compared to $\sqrt{\lambda l}$. (Van de Hulst 1981, p. 21)

A.2. Zone plates

Irradiance at a focus is amplified by a factor of 4 by the selection of the light from the first Fresnel zone alone. This amplification is compensated by a concentration of power on Airy's disk in the focal plane, so as to preserve energy conservation. If $I_1(q)$ is the irradiance due to diffraction of a plane wave by the first Fresnel zone ($r_1 = \sqrt{\lambda L}$), at distance q from the axis in the focal plane,

$$I_1(q) = I_1(0) \left[2 \frac{J_1(z)}{z} \right]^2 \quad (\text{A12})$$

$$\left(z = kr_1 \frac{q}{L} = 2\pi \frac{q}{\sqrt{\lambda L}} \right) \quad (\text{A13})$$

J_1 is the Bessel function of the first kind of order 1.

At the focus light concentrates over an area $Q_1 = \frac{3.65}{\pi} \lambda L$ delimited by the first minimum ($z = 3.83$, $q_1 = \frac{1.91}{\pi} \sqrt{\lambda L}$) of $|J_1(z)/z|$. The power across the spot is

$$\begin{aligned} P_1 &= I_1(0) \int_{z=0}^{z=3.83} \left[2 \frac{J_1(z)}{z} \right]^2 2\pi q dq \\ &= \left[\frac{\lambda L}{\pi} \int_0^{3.83} \frac{J_1(z)^2}{z} dz \right] I_1(0) \\ &\simeq \frac{0.4}{\pi} \lambda L I_1(0) = \frac{1.6}{\pi} \lambda L I_0 \end{aligned} \quad (\text{A14})$$

The power P_1 crossing the spot, contrary to the irradiance ($I_1 = 4I_0$ at the focus), depends on the area of Fresnel zones, and is concentrated towards the focus. The total power on Q_1 is less than the power ($\pi \lambda L I_0$) crossing the Fresnel zone, which ensures energy conservation.

Irradiance at the focus can be increased even more by adding the cooperative disturbances from Fresnel zones of same parity. A zone plate comprising N zones of same parity yields a theoretical irradiance at the focus $I_N(0) = N^2 I_1(0) (= 4N^2 I_0)$, and amplifies the irradiance by a factor $\propto N^2$. Since the 1950s zone plates with hundreds of Fresnel zones are currently realized in laboratory. A zone plate with 500 zones for instance amplifies the irradiance by a factor 10^6 .

The counterpart for this high increase of the irradiance is a concentration of the power crossing the focal plane on a limited area, s_N , around the focus. Should the irradiance at the focus apply over s_N ,

$I_N(0)s_N = \alpha_N P_N$, where α_N is large enough and $P_N = NP_1 = NS_1 I_0$ is the power flowing through the zone plate. Since $I_N(0) = N^2 I_1(0) = 4N^2 I_0$, s_N must be of order S_1/N , thus decrease as $1/N$.

Zone plate theory (Boivin 1952; Childers & Stone 1969) shows that the distribution of light in the focal plane of a zone plate continues to be well approximated by the Airy diffraction pattern of a circular aperture having the size of the zone plate⁷ (radius $a = r_{2N-1}$).

For illumination by a plane wave, $a = \sqrt{(2N-1)\lambda L} \simeq \sqrt{2N\lambda L}$ (for N large). The total area the zone plate occupies is $S_{2N} = 2\pi N\lambda L$. The efficient area (which leaves light go through) is half ($\pi N\lambda L = NS_1$). The irradiance at distance q from the axis in the focal plane is

$$I_N(q) \simeq I_N(0) \left[2 \frac{J_1(z)}{z} \right]^2 \quad (\text{A15})$$

with

$$z = kr_{2N-1} \frac{q}{L} = 2\pi q \sqrt{\frac{2N}{\lambda L}} \quad (\text{A16})$$

The radius of the bright focal spot ($z = 3.83$) is $q_N = \frac{1.91}{\pi} \sqrt{\lambda L / (2N)}$. The spot area, $Q_N = \frac{3.64}{\pi} \lambda L / N$, increases with the area of the zone plate and diminishes as $1/N$.

The power P_N across the focal spot is calculated as for Eq. A14. It can alternatively be expressed as a function of the irradiance at the focus $I_N(0)$, of the power that would be measured across the bright spot if there was no zone plate $Q_N I_0$, or of the power across the zone plate $S_N I_0$,

$$\begin{aligned} P_N &= \left(\frac{0.54}{\pi^2} Q_N \right) I_N(0) \\ &= \frac{2.15}{\pi^2} N^2 Q_N I_0 = \frac{0.4}{\pi^2} S_N I_0 \end{aligned} \quad (\text{A17})$$

The power P_N an observer measures over Q_N varies as N^2 times the power that would be measured without the zone plate. It nevertheless remains in proportion of N in absolute value: the $\propto N^2$ growth of the irradiance at the focus is compensated by the $1/N$ decrease, anticipated above, of the area of the bright spot. Energy conservation is ensured since the power crossing Q_N remains in a constant ratio ($\ll 1$) with the power on the zone plate.

These results, derived under a far-field hypothesis, mean that diffraction by a zone plate tends to align the direction of the diffracted light with the direction of the source wave, and focalize its power in the same direction. A significant fraction of the power lays within a solid angle $\Omega_N = Q_N / L^2 = 2\lambda / (\pi N L)$.

Eqs. A14 and A17 show that the power at the focus increases with the size of the zone plate. It suggests that a zone plate that would be realized on an astronomical scale (a few hundred pcs away), would concentrate an impressive power over a relatively large area at the observer position.

A.3. Diffraction by obstacles (particles or apertures) with dimensions small compared to the wavelength

Lorentz's atomic dipoles are probably what matches best the idea of Fresnel's oscillators. Unlike areas δS with size comparable to the wavelength, dipoles have a nearly (within a factor of 2 between the back and forward directions) isotropic phase function and the disturbance they create depends on wavelength as $1/\lambda^2$ (instead of $1/\lambda$), $1/\lambda^4$ for the irradiance (Van de Hulst 1981; Stone 1963).

Theory also shows that the extension of Eq. A10 to apertures small compared to the wavelength fails (Bethe 1944). A very small area diffracts with the same $1/\lambda^2$ wavelength dependence (for the disturbance) as a dipole. The disturbance due to a small dipole or aperture is $\propto \lambda^{-2} a^3$ (irradiance $\propto \lambda^{-4} a^6$), where a is the typical dimension of the dipole/aperture.

⁷The property can be understood for large N , because of the diminution of the thickness of Fresnel rings of high order.

To ensure continuity between the two regimes several small diffracting obstacles/apertures covering a larger area of order λ^2 should give back the forward disturbance of Eq. A10. This will happen only if a thickness of order λ is attributed to Huygens-Fresnel wavefronts and if the a^3 term in the disturbance due to dipoles is interpreted as corresponding to the volume δV of the dipoles. The forward disturbance created at a focus by small apertures or obstacles with sizes up to the wavelength is then $\delta u \propto \lambda^{-2} \delta V$ (since $\delta S \sim \delta V / \lambda$ in Eq. A10).

Under these conditions $N = \delta S / a^2$ small apertures, each with area a^2 and thickness λ , behave, as expected, as the larger area $\delta S \sim \lambda^2$. In a similar way $N \sim (\lambda/a)^3$ dipoles create the same disturbance in the forward direction ($\propto \lambda^{-1} \delta S \sim \lambda$, Eq. A10) as an elementary area $\delta S \sim \lambda^2$ of a wavefront.

If a thickness of order λ is attributed to wavefronts, the oscillator strength per unit area of Fresnel's hypothetical molecules satisfies (see Sect. 11.2) $(2\pi/\lambda)^2 \alpha_F (\lambda N_F) \simeq 1/\lambda$ and therefore $18\pi^2 n_F a_F^3 \simeq 1$, with n_F and a_F the density and radius of the dipoles (of polarizability $\alpha_F \simeq \frac{9}{2} a^3$).